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METHOD OF CALCULATION OF ANNUAL OVERALL EFFICIENCY OF MODERN WIND-POWER PLANTS

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16. Abstract

A method of calculation of annual overall efficiency of modern wind power plants equipped with asynchronous generators taking into account annual velocity duration curve at Den Helder, Holland, is presented. A comparison is made between variable pitch windmotor and fixed blade windmotor equipped with movable flaps. A careful calculation is recommended in view of rather small difference in efficiency of both systems.

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METHOD OF CALCULATION OF ANNUAL OVERALL EFFICIENCY OF MODERN WIND-POWER PLANTS

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In the preliminary studies for construction of a modern American wind motor with rotating blades at Grandpa's Knob - a project which came to grief in 1945 due to a material rupture in one of the rotating blades - the possibility of making the blades themselves non-rotatable and providing rotating control flaps instead was considered. The wind motor engineers did not work out the design in detail, probably because it had already been thought that a substantially lower efficiency was to be expected of blades with control flaps than with a wing turning as a whole [1]. /137*

In connection with the recent revival of interest in the utilization of wind energy for generating electricity, it is worthwhile to take another look at what the difference in output between the two blade designs would amount to. In doing this, we will not compare the efficiency figures of both wind wheel designs with each other at the same wind velocities and rpm's, but we will compare the annual output, expressed by the fraction

$$\frac{E}{W} = \frac{\text{annual delivered kWh of electricity}}{\text{annual wind kWh usable in practice}},$$

of one design with that of the other. Here, the influence of the annual velocity-duration curve of the wind - which differs from location to location - must be taken into account. This annual velocity-duration curve, e.g. for Den Helder at a height of 50 meters above ground - derived from K.N.M.I. data - is represented by the curve v) shown in Figure 1. For each wind velocity V, this gives the operating time h as a percentage of the number of hours in a year that wind velocities equal to or greater than V are available at the point in question, hence V = f(h). The

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wind power curve $L_w = f(h)$ can easily be derived from this annual velocity-duration curve, with the aid of the familiar formula

$L_w = \frac{F \cdot V^3}{1600} = f(V)$, in which

L_w = available wind power in kW,

F = area of wind wheel circle in m^3 [sic],

V = wind velocity in m/sec.

This wind power function $L_w = f(V)$ is given in Figure 1 for a 400 m^2 wind wheel circle (for a wind wheel diameter of 22.5 m) by curve $\widehat{w}$. With this curve $\widehat{w}$ and curve $\widehat{v}$ it is easy to find the curve w' represented by $L_w = f(h)$ in Figure 1.

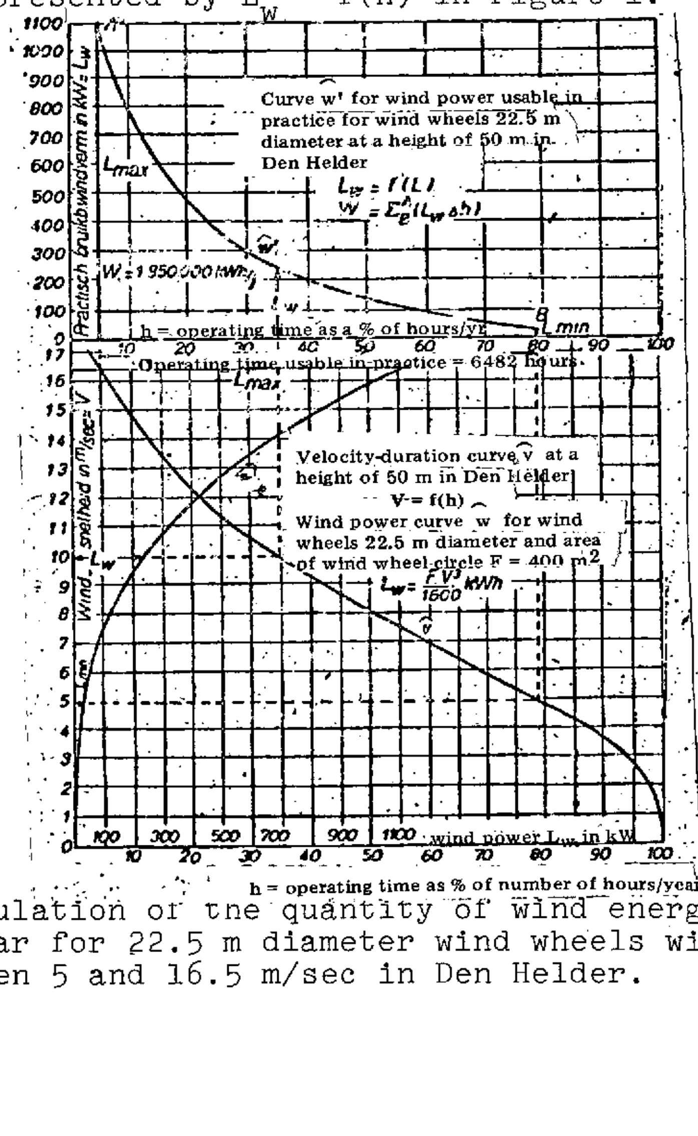

Figure 1. Calculation of the quantity of wind energy usable in practice per year for 22.5 m diameter wind wheels with wind velocities of between 5 and 16.5 m/sec in Den Helder.

If we now determine the area enclosed between the operating time axis and the above-mentioned wind power curve w'), we obtain the theoretically available wind kWh per year for a wind wheel diameter of 22.5 m. However, it is known that only a part of this theoretically available quantity of energy can be used in practice, namely that part bounded on the one hand by the wind velocity V_{min} in which the given axis power is just sufficient to cover mechanical non-load losses of the whole system and has an upward boundary of the wind velocity V_{max} at which the wind wheel must be stopped to avoid equipment overload. If we assume that V_{min} is 5 m/sec and that V_{max} is 16.5 m/sec, we can determine points A and B of the wind power curve, which given the minimum and maximum usable wind powers /138

$$L_{min} = \frac{F}{1600} V_{min}{}^3 \text{ and } L_{max} = \frac{F}{1600} V_{max}{}^3.$$

The area between the wind power curve and the operating time axis delimited by the two ordinates passing through points A and B represents the annual wind energy usable in practice.

By planimetry we can find that the quantity of wind energy usable in practice amounts to 1,850,000 kWh/year for a wind wheel of 22.5 m diameter in Den Helder.

We will now have to calculate how much mechanical energy is taken from the wind by the 22.5 meter diameter wind wheel in a year and added to the generator axis, and how much electrical energy can be delivered by the generator connected with it. In the design on which this calculation is based, the choice of generator plays a preponderant role.

As is known, three types of generators are used in modern wind power plants: the DC generator whose rpm is approximately proportional to the wind velocity, the synchronous generator with a constant rpm, and the asynchronous generator with a full-load rpm 10% to 12% greater than the no-load rpm.

In the calculation below, only wind power plants equipped with asynchronous generators with a full-load rpm of 12% above no-load or synchronous rpm's will be taken into consideration. In order to calculate the electric power delivered by such a system, the extension or full-load power of the generator must first be considered. For the above-mentioned wind wheel with modern wind profile blades of 22.5 meters diameter mounted at a height of 50 meters in Den Helder we can, for example, take a full-load power at the generator terminals of 130 kW with a wind velocity of 11 to 12 m/sec as a starting point. If we put the useful effect of the generator at full load at 86%, a generator axis-driving power of $\frac{130}{0.86}$ = 152 kW is necessary. We will now assume that the mechanical transmission and control apparatus absorb a constant power of 8 kW, when, at generator full load, a power of about 160 kW at the mill axis must be delivered. Moreover, we can say that the mill axis must be able to deliver the no-load power of 8 kW at as low a wind velocity as 5 m/sec. On the basis of the latter assertion we can easily calculate, with the aid of the above-mentioned formula $L = \frac{F}{1600} V^3$ that the wind power at 5 m/sec velocity amounts to 31.25 kW and accordingly the efficiency of the wind wheel $\frac{8}{31.25}$ must be about 0.25 with this wind velocity.

In order now, using the above data, to calculate how much electrical energy can be delivered per year by the wind power plant, it is useful, in the first place, for the efficiency curve of the wind wheel as a function of wind velocity and accordingly the efficiency of the generator as a function of the assumed axis power to be known.

In Figure 2, curve I gives the efficiency C_1 of a modern three-blade wind wheel model with rotating blades as a function

of the revolving speed coefficient $\sigma = \frac{\text{speed of revolution } U}{\text{wind velocity } V}$,
which curve is derived from the model tests conducted in Professor Ackeret's laboratory in Zurich on a wind wheel model, also drawn in Figure 2 [2]. It can be assumed that the efficiency curve of a wind wheel will be greater since the scale effect will probably be somewhat larger, but this calculation will not take this into account. Moreover a curve II is drawn in Figure 2 which gives the efficiency of a wind wheel model of the same shape with fixed blades and an angle of attack β equal to 8° at

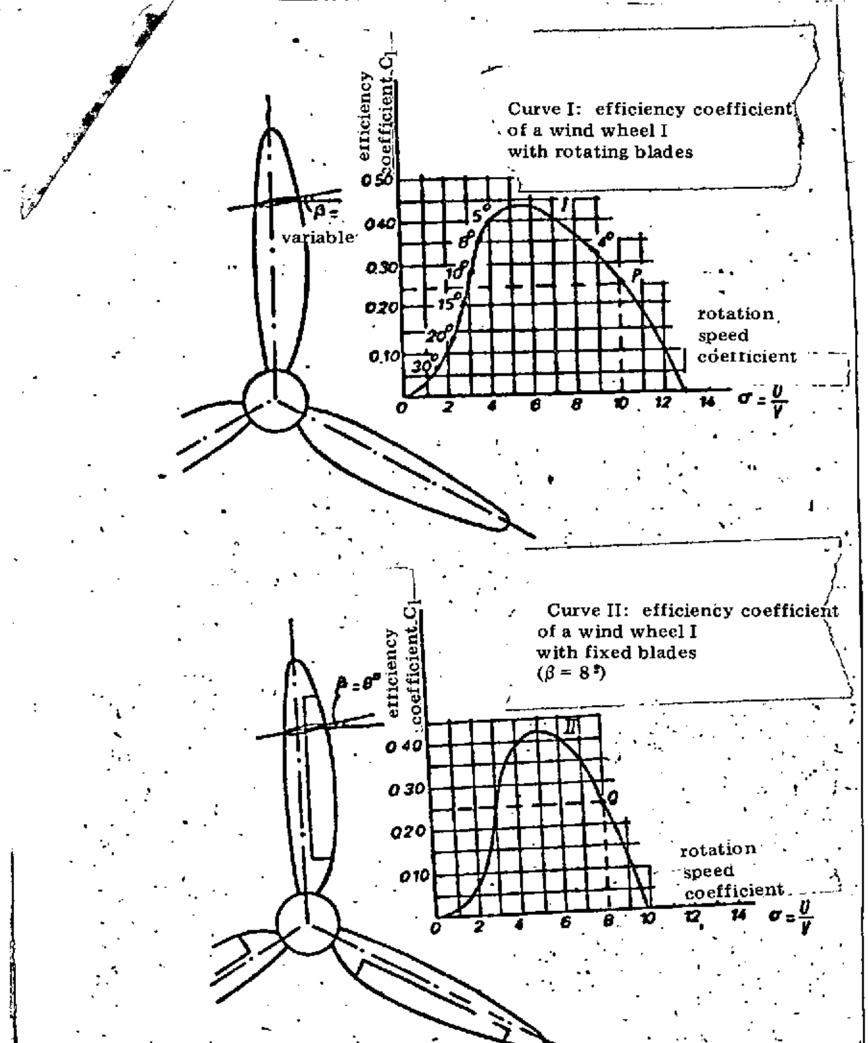

Figure 2. Efficiency coefficients of wind wheels I and II.

a distance of 0.36 diameter from the axis, derived from the same tests. The wind wheel model with this angle of attack is also shown in the figure, where the possible form of the control is given. /139

To convert lines I and II into efficiency lines as a function of wind velocity, the starting point is the calculated efficiency of 0.25 that the wind wheel must have with a 5 m/sec wind velocity in order to cover the mechanical losses. On both curves I and II we can easily find the points P and Q where the useful effect of 0.25 is reached on the downward slopes of these curves, where the values $\sigma = 10$ for the wind wheel with rotating blades and $\sigma = 8$ for the fixed-blade wheel belong. From these σ values the speeds of rotation $U_1 = 5 \times 10 = 50$ m/sec and $U_2 = 5 \times 8 = 40$ m/sec can be found, in which the axis power of each wind wheel amounts to 8 kW. To calculate the efficiency values from curves I and II with higher wind velocities, we can determine the descending values of σ for a number of ascending values of V by taking a U value for each V value. This U value is not constant, as with a wind wheel coupled to a synchronous generator, but it varies from 1 to 1.12 of the no-load values in the wind wheel considered here, which is coupled to asynchronous generators. It is easiest to take a specific parameter value $U = p$ and then with the aid of the formula $V = \frac{U}{\sigma}$ to determine the new curve $C_L = 8(V)$ from the known efficiency curve $C_L = f(\sigma)$. If we do this for three different parameter values, e.g. U = 50, 53, and 56 for wind wheel I and U = 40, 42.5, and 45 for wind wheel II, we obtain three curves $C_L = f(V)$ for wind wheel I and three curves for wind wheel II. The outer envelope of such a three-curve set then represents the general function $C = f(V)$ of the wind wheel in question. These functions for wind wheel I are given in Figure 3 by curve $\widehat{a}$ and in the same way curve b gives the function for wind wheel II. From these curves we can also derive the axis power curves $L_a = f(V)$ with the aid of the formula $L_a = \frac{C_L \cdot F}{1600}$. These are curves $\widehat{c}$, and $\widehat{d}$ in Figure 3.

When we look at these curves, we can see that they both reach the maximum permissible axis power of 160 kW between 11 and 12 m/sec wind velocity. To take away energy from winds up to 16.5 m/sec, we must feather the wind wheel, i.e., artificially decrease the efficiency so that even with stronger winds no more than 160 kW axis power will be delivered. This feathering can be done with the rotating-blade wind wheel by giving a greater pitch to the blades than is normally required for favorable wind use. For the fixed-blade wind wheel the feathering is done by the control flaps, which, until feathering velocity is reached, lie inside the blade profile, being turned outward, whereby the efficiency is artificially decreased.

If we wish the axis power of the wind wheel from the feathering velocity to the maximum usable wind velocity of 16.5 m/sec to remain constant at 160 kW, then we can very simply find the feather portion of the efficiency curves for each value of V greater than the feathering velocity by calculating the value of c_I from the formula: $c_I = \frac{160 \cdot 1600}{F \cdot V^3}$. The feathering parts of the efficiency curves are represented in Figure 3 by dashed lines. The feathering parts of the axis power curves are shown in the same figure by lines drawn at an equal distance from the V axis with an abcissa of 160 kW. To give an idea of the magnitude of pitch change which the rotating blades of wind wheel I must undergo between 5 and 16.5 m/sec wind velocity, the values of the variable angle of attack β - derived from efficiency curve I in Figure 2 - are transferred to efficiency curve $\widehat{a}$ of Figure 3. It can be seen here that the pitch angle with increasing wind velocity starts by being very small until a wind velocity of 11.3 m/sec is reached. After this, the pitch must be substantially greater (from 5° to 19°) to keep the axis power constant at 160 kW until the maximum usable wind velocity of 16.5 m/sec is reached. Since when wind wheel I is in operation dangerous equipment overloads may occur with even higher wind velocities, the wind wheel must be stopped at the threshold velocity of 16.5 m/sec by turning the blades into the so-called vane position, i.e., by making β equal to 90°, whereby the wind drive torque and the axial pressure force on the wind wheel are practically zero. For wind wheel II, equipped with control flaps, we can also determine the position of the control flaps experimentally and give this position with different wind velocities above the feathering velocity (12 m/sec for wind wheel II) on the efficiency curve b) of this wind wheel by the value of the pitch angle.

Since thus far no satisfactory data on the operation of control flaps in modern wing-shaped blade profiles are known, the values of the flap pitch angle are left out in Figure 3. However, it is clear that with wind wheel II also, above 16.5 m/sec the control valves must be in such a position that the wind drive torque is also practically equal to zero and the wind wheel is /140 thus stopped.

Returning to the task of calculating the annual efficiency for both wind wheels, we can first convert the axis power curves $L_a = f(V)$, represented by lines $\widehat{c}$ and $\widehat{d}$ in Figure 3, into new axis power curves $L_a = f(h)$ with the aid of the velocity-duration curve $V = f(h)$ of Figure 1, transferred to Figure 3 for the sake of convenience. We then obtain lines $\widehat{c'}$ and $\widehat{d'}$ in the same figure, given by the wind wheel axis powers as a function of the operating time as a percentage of the number of hours in a year. In order to find the generator axis power as a function of operating time, we must decrease the wind wheel axis power by a constant amount of 8 kW, which is necessary to cover the mechanical losses in the gear transmission and control apparatus. With the generator axis power values thus found the generator efficiencies are given as percentages in curves c' and d' of Figure 3. These generator efficiencies are derived from various data in the literature on asynchronous generators. If we finally multiply the generator axis powers with the associated efficiencies, we find the delivered electric power L_g as a function of the operating time, represented by curves e and f in Figure 3. The parts of these curves uable in practice is limited by points S and T, which were found from the points with V = 5 and V = 16.5 on the velocity-duration curve. Now, the area between a power curve L_g and the operating time axis, limited by the ordinates of points S and T, represents the annual delivered electrical energy E in kWh. If we now use planimetry to measure the areas between the power curves and the operating time axis for wind wheels I and II, we find an annual delivered electrical energy qualtity of 454,700 kWh for wind wheel I and 432,000 for wind wheel II. If, finally, we calculate the respective output from these quantities and the wind energy usable in practice already found, we get the following results:

Annual Output Wind Wheel I = 24.58%
Annual Output Wind Wheel II = 23.35%

If, with these figures before us, we wish to determine which wind wheel design is to be preferred, the relatively small difference in output is not a decisive justification for choosing design I. We need to remember that the installation and operating costs (finance charges, servicing, and maintenance) of wind wheel I with rotating blades, as a consequence of the complex design, will undoubtedly be higher than those of wind wheel II, which is equipped merely with simple control flaps. We must therefore investigate whether the higher operating costs of wind wheel I are sufficiently compensated for by the higher electricity output revenues in comparison with wind wheel II.

Without careful installation and operating estimates the above question cannot be answered with any certainty. However, we can positively recommend - in view of the slight difference in annual output - that both the design with rotating blades and that with control flaps must be thoroughly investigated when designing a modern wind power plant.

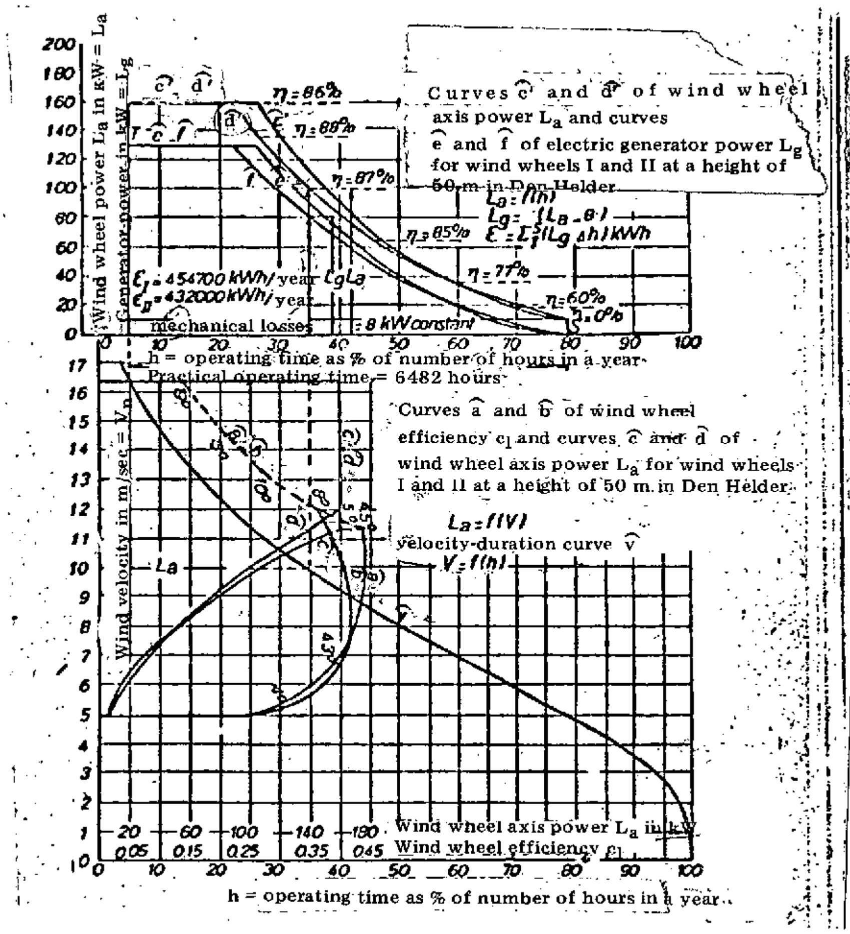

Figure 3. Calculation of quantity of electrical energy delivered per year by wind wheels I and II.

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